

Exotic hadron spectroscopy at the LHCb experiment

G. A. Cowan, on behalf of the LHCb collaboration

School of Physics and Astronomy, University of Edinburgh, EH9 3FD, UK

The LHCb experiment is designed to study the decays and properties of heavy flavoured hadrons produced in the forward region from proton-proton collisions at the CERN Large Hadron Collider. During Run 1, it has recorded the world's largest data sample of beauty and charm hadrons, enabling precise studies into the spectroscopy of such particles, including discoveries of new states and measurements of their masses, widths and quantum numbers. An overview of recent LHCb results in the area of exotic hadron spectroscopy is presented, focussing on the discovery of the first pentaquark states in the $\Lambda_b^0 \rightarrow J/\psi p K^-$ channel and a search for them in the related $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ mode. The LHCb non-confirmation of the D0 tetraquark candidate in the $B_s^0 \pi^+$ invariant mass spectrum is presented.

1 Introduction

Exotic hadrons are defined as hadrons having internal structures more complex than the $q\bar{q}$ mesons or qqq baryons systems in the quark model. Since 2003 when the $X(3872)$ state was discovered by the Belle collaboration¹ the search for and study of new exotic particles has become a hot topic since, spurred on by a wealth of new data from many particle collider experiments. This data has allowed the mass, width and quantum numbers of many states to be measured and new states discovered. However, the lack of any clear pattern necessitates a new programme of experimental and theoretical study to understand the strong interaction dynamics that can cause their production and structure.

These proceedings will discuss recent results from the LHCb collaboration in the area of exotic hadron spectroscopy, focussing on the recent pentaquark observation in the $\Lambda_b^0 \rightarrow J/\psi p K^-$ channel and a new model-independent analysis to further support the case for the exotic nature of this state. Evidence for exotic structures in the Cabibbo suppressed $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ mode will be presented as will the non-confirmation of an exotic resonance in the $B_s^0 \pi^+$ invariant mass spectrum. Further information on exotic hadron spectroscopy can be found in Ref.².

2 Pentaquark observation

Figure 1 (a) shows the distribution of $m(J/\psi p K^-)$ from the selected $\Lambda_b^0 \rightarrow J/\psi p K^-$ candidates³ in the LHCb Run 1 sample. There are approximately 26000 signal events with a 5.4% background within a 2σ window around the known Λ_b^0 mass. A six-dimensional amplitude model is constructed to fully describe the structure of the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay. All known $\Lambda^* \rightarrow p K^-$ states and two exotic $P_c^+ \rightarrow J/\psi p$ states are included in the model, with their line shapes being described using relativistic Breit-Wigner functions. Fully simulated events are used to correct for the detector and selection efficiencies. The amplitude model containing only Λ^* resonances is insufficient to describe the data and two interfering P_c^+ states with opposite parity are required (see Figure 1 (b)) both of which are statistically significant at larger than 9σ , evaluated using

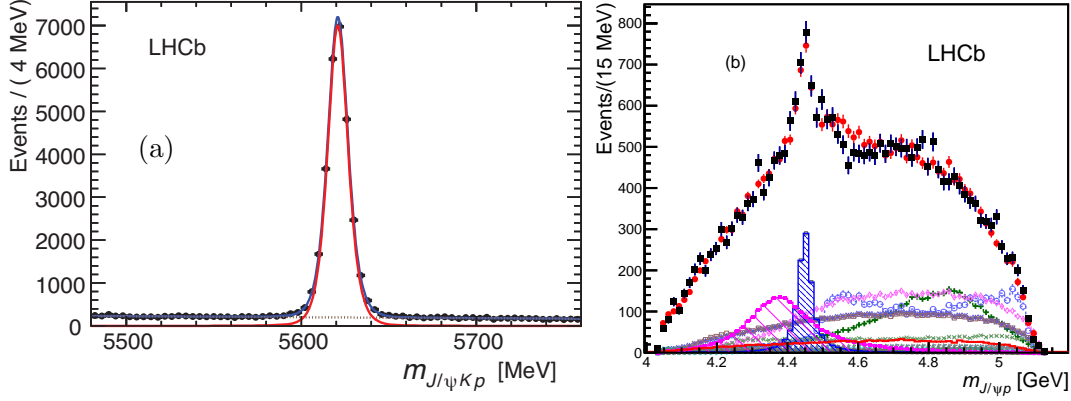


Figure 1 – (a) Distribution of $m(J/\psi pK)$ for selected $\Lambda_b^0 \rightarrow J/\psi pK^-$ candidates (black points) and the fit projection. (b) Fit projections for $m(J/\psi p)$ for the reduced Λ^* model with two P_c^+ states. The data are shown as solid (black) squares, while the solid (red) points show the fit. The solid (red) histogram shows the background distribution. The (blue) open squares with the shaded histogram represent the $P_c(4450)^+$ state and the shaded histogram topped with (purple) filled squares represents the $P_c(4380)^+$ state. Each Λ^* component is also shown.

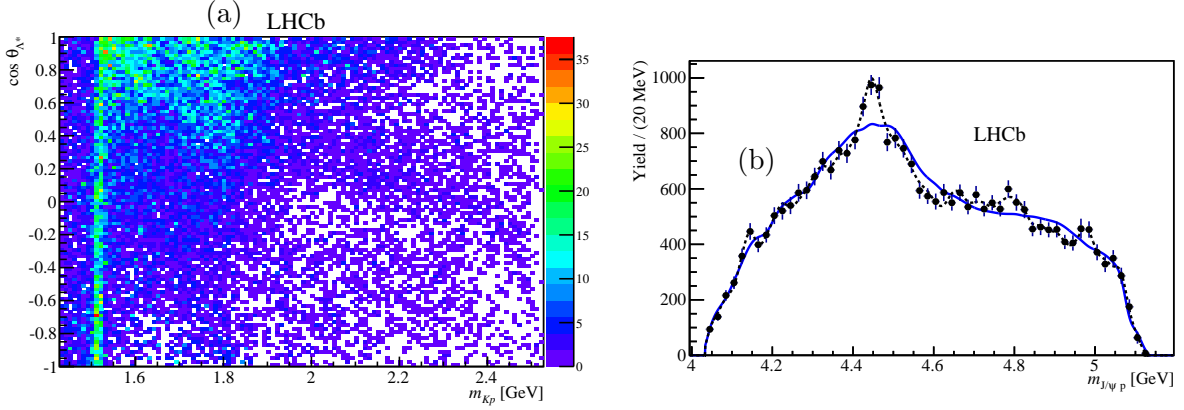


Figure 2 – (a) Background-subtracted and efficiency-corrected distribution of the cosine of the Λ^* helicity angle versus $m(Kp)$. (b) Efficiency-corrected and background-subtracted $m(J/\psi p)$ distribution of the data (black points), with $\mathcal{F}(m_{J/\psi p}|H_0)$ (solid blue line) and $\mathcal{F}(m_{J/\psi p}|H_0)$ (dashed black line) superimposed.

pseudoexperiments. The low mass state ($4380 \pm 8 \pm 29$ MeV) is wide ($205 \pm 18 \pm 86$ MeV) with $J^P = 3/2^-$ and a fit fraction of $(8.4 \pm 0.7 \pm 4.2)\%$ while the high mass state ($4449.8 \pm 1.7 \pm 2.5$ MeV) is narrow ($39 \pm 5 \pm 19$ MeV) with $J^P = 5/2^+$ and a fit fraction of $(4.1 \pm 0.5 \pm 1.1)\%$. Other J^P combinations give similar fit qualities. The main systematic uncertainties in the result come from the limited knowledge of the Λ^* spectrum.

The case for the exotic nature of the P_c^+ contributions to the $\Lambda_b^0 \rightarrow J/\psi pK^-$ channel is strengthened via a model independent analysis in Ref. ⁴ in which no assumption is made regarding the number and type of Λ^* resonances. Instead, the analysis simply tries to answer the question if the structure observed in the distribution of $m(J/\psi pK^-)$ can be explained via reflections from the interfering Λ^* states that are visible in $m(pK^-)$. Only physical arguments are employed to restrict the maximal Λ^* spin that can contribute at a given value of $m(pK^-)$. Figure 2 (a) shows the two-dimensional Dalitz plot of the $\Lambda_b^0 \rightarrow J/\psi pK^-$ data, which is decomposed into a set of Legendre polynomials. These polynomials are then used to weight the phase-space simulated $\Lambda_b^0 \rightarrow J/\psi pK^-$ sample to see if it can reproduce the $m(J/\psi pK^-)$ distribution in Figure 2 (b). Pseudoexperiments are generated to build a statistic that can be used to test the null hypothesis that only Λ^* resonances are required. These find that in the data, the null hypothesis is ruled out at more than 9σ .

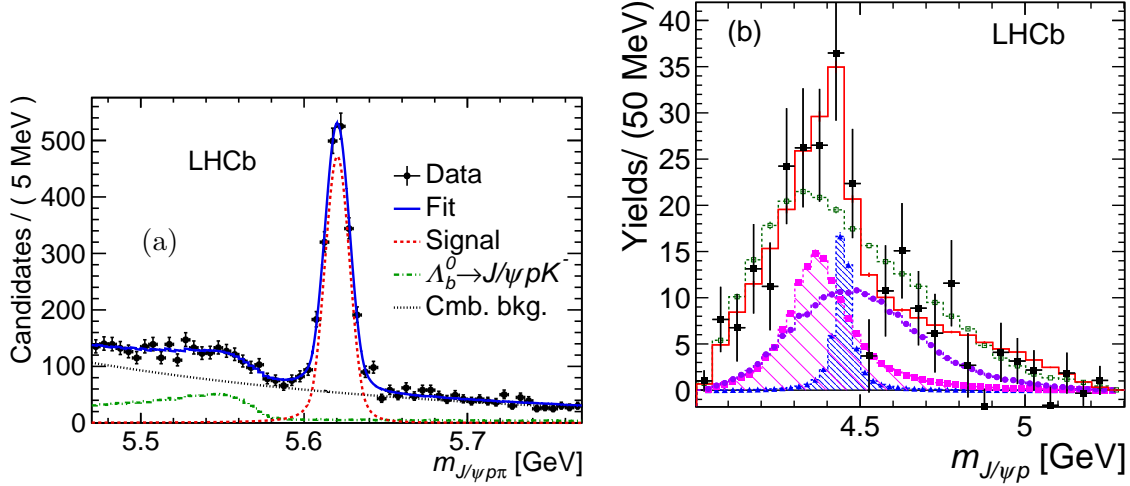


Figure 3 – (a) Distribution of $m(J/\psi p \pi^-)$ for selected $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ candidates (points) and the fit projection. (b) Background-subtracted data (black points) and total fit (red line) projections onto $m(J/\psi p)$ for the region with $m(p \pi^-) > 1.8$ GeV. The N^* -only model is shown by the green histogram, which is clearly not a good fit to the data. The $P_c(4380)^+$, $P_c(4450)^+$ and $Z_c(4200)^-$ components are shown by the pink, blue and purple histograms, respectively.

3 Evidence for exotic hadron contributions to $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ decays

Following the observation of the P_c^+ states described above, it is important to search for other production and decay modes in order to help understand if they are genuinely exotic baryons or perhaps some sort of kinematical effect⁷. In Ref.⁹ the LHCb collaboration has observed the Cabibbo suppressed $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ decay and measured its branching ratio to the Cabibbo favoured mode to be approximately 8%. As described above, an amplitude model is constructed to describe the three mutually interfering decay chains ($\Lambda_b^0 \rightarrow J/\psi N^*(\rightarrow p \pi^-)$, $\Lambda_b^0 \rightarrow P_c^+(\rightarrow J/\psi p) \pi^-$ and $\Lambda_b^0 \rightarrow Z_c^-(\rightarrow J/\psi \pi^-) p$), which is then fit to the approximately 1900 signal events that are isolated using the $m(J/\psi p \pi^-)$ distribution shown in Figure 3 (a). The fit model including only the well-established N^* states is insufficient to describe the data and show significant improvement when exotic contributions are included. When all three exotics are included (taking their parameters from Refs.³ and ¹⁰) there is 3.1σ evidence, with their fit fractions measured to be $(5.1 \pm 1.5^{+2.1}_{-1.6})\%$ ($P_c(4380)^+$), $(1.6^{+0.8+0.6}_{-0.6-0.5})\%$ ($P_c(4450)^+$) and $(7.7 \pm 2.8^{+3.4}_{-4.0})\%$ ($Z_c(4200)^-$), which are consistent with those in Ref.³, accounting for the Cabibbo suppression. No single P_c^+ or Z_c^- component makes a significant difference to the model. Figure 3 (b) shows the distribution of $m(J/\psi p)$ for the region of high $m(p \pi^-)$ along with the fit projection. The main systematic uncertainties come from the knowledge of the exotic masses, widths, J^P and the knowledge about the content of the N^* spectrum.

4 Search for structure in the $B_s^0 \pi^+$ invariant mass spectrum

In Ref.¹¹ the D0 collaboration claimed evidence for a new state, the $X(5568)$, after finding an enhancement near threshold in the $B_s^0 \pi^+$ invariant mass spectrum and measuring the production fraction of this state to be $\rho = (8.6 \pm 1.9 \pm 1.4)\%$ of the B_s^0 meson production. Using a dataset twenty times larger than D0's, the LHCb collaboration performed a search¹² for the $X(5568)$ using very clean samples of $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow J/\psi \phi$ decays (see Figure 4(a)). Inspection of the $B_s^0 \pi^+$ mass distribution in various kinematical regimes did not show any evidence of an enhancement, allowing limits to be set on its production as $\rho_{PT}(B_s^0) > 10 \text{ GeV} < 0.021(0.024)$ at 90 (95)% confidence level. Limits were also placed as a function of the supposed mass and width of the X state.

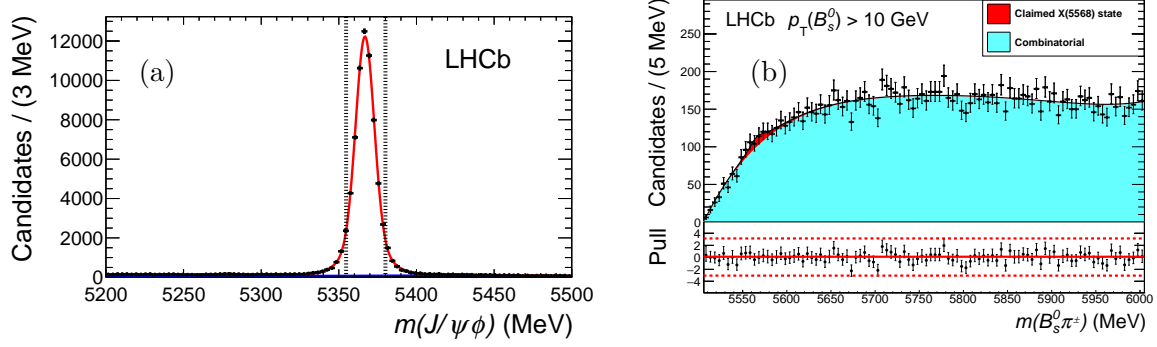


Figure 4 – (a) Selected $B_s^0 \rightarrow J/\psi\phi$ decays with $p_T(B_s^0) > 5$ GeV, where the B_s^0 signal window requirements are indicated by dotted lines. (b) Results of the fit to the $B_s^0\pi^\pm$ mass distribution for all candidates with $p_T(B_s^0) > 10$ GeV. The component for the claimed $X(5568)$ state is included in the fit but is not significant.

5 Summary

Recent results from the LHCb collaboration in the area of exotic hadron spectroscopy have been presented, showing more detailed studies of the pentaquark states discovered last year and evidence for their presence in a new decay mode. In addition, the LHCb collaboration has not confirmed the near-threshold enhancement in the $B_s^0\pi^+$ invariant mass spectrum, which was reported by the D0 collaboration.

Acknowledgements

I would like to thank the organisers of Rencontres de Blois for creating a very enjoyable conference atmosphere. I acknowledge support from STFC grant ST/K004646/1.

References

1. S. K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **91** (2003) 262001 doi:10.1103/PhysRevLett.91.262001 [hep-ex/0309032].
2. S. Stone, these proceedings.
3. R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001 doi:10.1103/PhysRevLett.115.072001 [arXiv:1507.03414 [hep-ex]].
4. R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002 doi:10.1103/PhysRevLett.117.082002 [arXiv:1604.05708 [hep-ex]].
5. B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. D **79** (2009) 112001 doi:10.1103/PhysRevD.79.112001 [arXiv:0811.0564 [hep-ex]].
6. R. Aaij *et al.* [LHCb Collaboration], JHEP **1407** (2014) 103 doi:10.1007/JHEP07(2014)103 [arXiv:1406.0755 [hep-ex]].
7. E. Wang, H. X. Chen, L. S. Geng, D. M. Li and E. Oset, Phys. Rev. D **93** (2016) no.9, 094001 doi:10.1103/PhysRevD.93.094001 [arXiv:1512.01959 [hep-ph]].
8. H. Y. Cheng and C. K. Chua, Phys. Rev. D **92** (2015) no.9, 096009 doi:10.1103/PhysRevD.92.096009 [arXiv:1509.03708 [hep-ph]].
9. R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082003 Addendum: [Phys. Rev. Lett. **117** (2016) no.10, 109902] doi:10.1103/PhysRevLett.117.082003, 10.1103/PhysRevLett.117.109902 [arXiv:1606.06999 [hep-ex]].
10. K. Chilikin *et al.* [Belle Collaboration], Phys. Rev. D **90** (2014) no.11, 112009 doi:10.1103/PhysRevD.90.112009 [arXiv:1408.6457 [hep-ex]].
11. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **117** (2016) no.2, 022003 doi:10.1103/PhysRevLett.117.022003 [arXiv:1602.07588 [hep-ex]].
12. R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) 152003 doi:10.1103/PhysRevLett.117.152003 [arXiv:1608.00435 [hep-ex]].